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MEASUREMENT OF HYSTERESIS VALUES FROM HIGH MAGNETIZING FORCES

BY

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By W. L. Cheney

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I. INTRODUCTORY

In general, experimenters using various modifications of the "isthmus method" have not been very successful in measuring hysteresis values. Ewing, who first developed the isthmus method,[1] used an entirely different method for measuring hysteresis values.

Campbell and Dye [2] describe a method for measuring the residual induction and the coercive force, but they do not publish any hysteresis data in their paper, hence no conclusions can be drawn regarding the value of the method.

The writer [3] in describing a method (a modification of the "isthmus method") suitable for the measurement of the normal induction of straight bars in intense magnetic fields, discussed also an attempt (not altogether successful) to measure hysteresis values. He has since improved his method so that more satisfactory results may be obtained. The purpose, therefore, of this paper is a description of this method.

II. APPARATUS

The apparatus consists essentially of a du Bois electromagnet with flat pole pieces separated by an air gap and pierced coaxially so that a rod may be extended through them and the electro-

[1] Ewing, Magnetic Induction in Iron and Other Metals.
[2] Campbell and Dye, Inst. of Elec. Eng. Journ., 54, p. 35; 1918.
[3] B. S. Scientific Papers, 15, p. 629; 1920.

magnet. Surrounding the specimen are three coaxial test coils wound on brass forms. When the inner coil is connected in series with a ballistic galvanometer, the normal induction is measured by the throw of the galvanometer upon complete reversal of the magnetizing current. After connecting either the inner and middle or middle and outer coils in series opposition, the value of the magnetizing force can also be determined ballistically.

By careful comparisons with normal induction data obtained on a standard apparatus it was found that the method yielded very satisfactory results. For hysteresis measurements, however, the method was not so successful.

III. PREVIOUS METHOD FOR MEASURING HYSTERESIS CONSTANTS

The specimen was magnetized with a force H_m (Fig. 1), the corresponding induction B_m being shown at the tip of the hysteresis loop. On complete reversal of the direction of the current in the electromagnet, the magnetizing force changed from H_m to $-H_m$ and hence the induction changed from B_m to $-B_m$. If, then, instead of reversing the current, the circuit was suddenly broken, H should have dropped to zero and B should have changed from B_m to B_r. It was found, however, that, on account of the small residual magnetism remaining in the core of the electromagnet, B_r was not quite reached, but instead a somewhat higher value B_a. For magnetically hard material B_a differs only slightly from the true value of the residual induction B_r, but for softer materials, having a greater slope of the hysteresis curve in this region, the discrepancy is greater.

The coercive force was determined in the following manner: The galvanometer was connected in series with the B coil and instead of completely reversing the magnetizing field H_m it was reduced (by adding a resistance R_c to the primary circuit simultaneously upon reversal of the current) to a small negative field H_c which was just sufficient to cause the induction to appear to change from B_m to O; that is, the galvanometer deflection was just one-half the total deflection corresponding to a change from B_m to $-B_m$.

Then, after connecting the galvanometer to either set of H coils and suddenly breaking the circuit, a reading was obtained which corresponded to a change of H from H_c to approximately zero, and was considered proportional to the coercive force. It was difficult to read the deflection very accurately in the case of mag-

netically soft materials owing to the small order of magnitude of the throw of the galvanometer which is hardly sensitive enough for such small values.

This method is essentially the same as that described by Campbell and Dye.[4] By comparison with data obtained with the Burrows permeameter[5] and with the Fahy Simplex permeameter,[6]

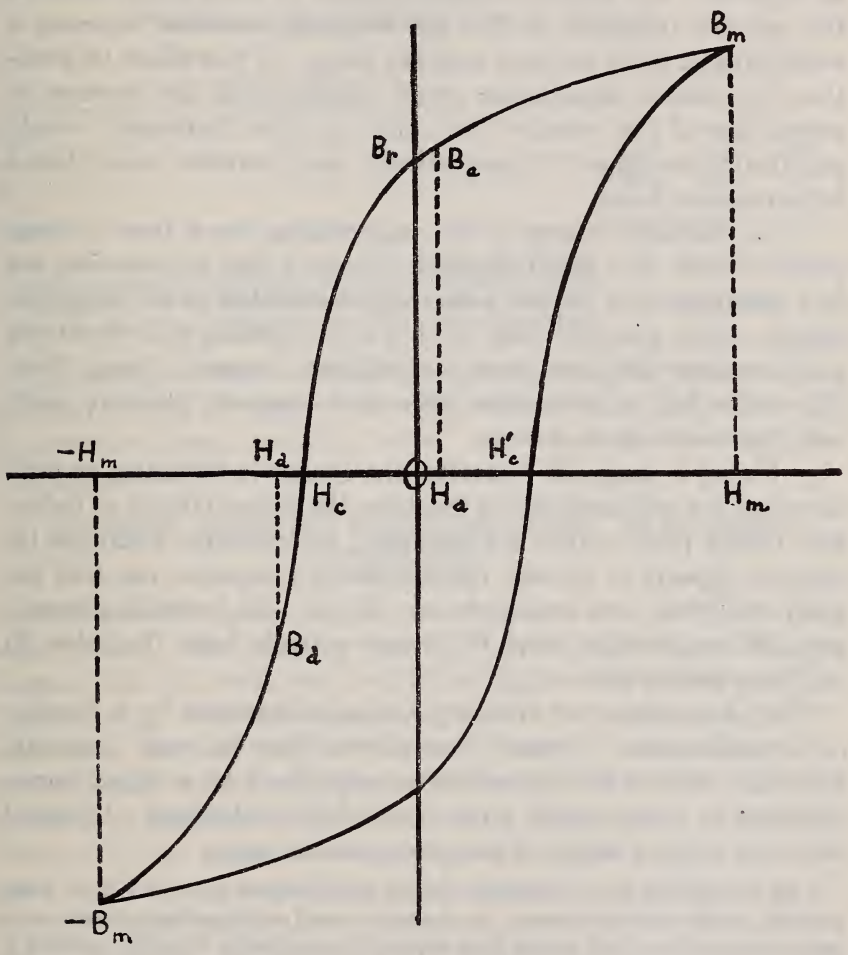

FIG. 1.—*Characteristic hysteresis loop*

results obtained by the method herein described were found to be too large, the difference being very small in the case of magnetically hard material having a large coercive force, but being about 100 per cent too large for very soft material.

[4] Campbell and Dye, Inst. of Elec. Eng. Journ., 54, p. 35; 1918.
[5] C. W. Burrows, B. S. Bulletin, 6, p. 31, 1909; Scientific Paper No. 117.
[6] F. P. Fahy, Chem. & Met. Eng., 19, pp. 247–250; 1918.

IV. POSSIBLE CAUSES OF ERRORS IN READING

The differences in comparative values, described above, may be due to a number of causes.

1. Owing to the small residual magnetism in the core of the electromagnet, the coercive force may not change from H_c to O, as supposed, but may be carried beyond to some small value in the opposite direction, so that the resulting deflection indicates a value greater than the true coercive force. If this effect be additive, its relative importance would decrease with the increase in magnitude of the coercive force; that is, the discrepancy would practically disappear for magnetically hard material which has a large coercive force.

2. In suddenly changing the magnetizing force from a large positive value to a small negative value the field surrounding the test specimen may be less uniformly distributed in the space included within the test coils, so that upon opening the circuit the galvanometer deflection does not indicate a correct change from H_c to zero but to some other value and does not, therefore, indicate the true coercive force.

3. Owing to magnetic viscosity, the change in induction as indicated by the galvanometer is less than the actual change of induction taking place within the specimen; for example, when the induction appears to be zero (galvanometer deflection, one-half the total deflection for a change from $+B_m$ to $-B_m$) resulting from a negative magnetizing force H_c it may actually have the value B_d resulting from a force H_d.

This phenomenon of viscosity has been described by a number of experimenters. Ewing[7] has shown that in weak magnetic fields soft iron is not immediately magnetized to a degree corresponding to the magnetic force to which it is subjected. Jouaust,[8] who has made a study of the phenomenon, says:

> If the magnetizing field is suddenly changed from its value $+H$ to a value h, then, generally, as the result of viscosity, the deflection δ read on the ballistic galvanometer is weaker than that which should have appeared in conformity with the variation of flux which has been produced. And indeed, if, after having waited a few moments, the magnetizing field is varied from h to $-H$, one observes a deflection δ_2 such that $\delta+\delta_2$ is less than the deflection Δ, observed in passing from $+H$ to $-H$. But if we shift the magnetic field from h to $+H$ (corresponding to a condition of saturation), as the phenomenon of lag is not produced, the deflection δ_1, read on the ballistic galvanometer, is a good indication of the variation of flux which has taken place, and which is equal to that which should have been measured; in which case, we have, as might be expected, $\delta_1+\delta_2=\Delta$.

[7] Ewing, Magnetic Induction in Iron and Other Metals, p. 122.
[8] Jouaust, Trans. Elec. Cong., St. Louis, 1, p. 470; 1904.

Table 1 is taken from Jouaust's paper. Column 1 gives the actual variations of flux produced (δ_1); column 2, the variations estimated from the ballistic deflections when the variation is suddenly produced (δ_2); and column 3, when this process is divided up into about 15 successive operations, the value of the maximum of the field being in all cases 98 gausses.

TABLE 1.—Effect of Magnetic Viscosity (Jouaust)

H (Gausses)	[a]1	[b]2	[c]3
+1.1	8000	7700	7650
+ .7	8720	8200	8300
0	10 500	9600	9850
− .7	13 700	11 700	12 200
−1.1	17 850	13 650	14 750

[a] Actual variations of flux produced in passing from H to $H_{max}=98$ gausses.
[b] Variations estimated from ballistic deflections when variation is suddenly from $H_{max}=98$ gausses.
[c] Same as 2, when process is divided up into about 15 successive operations.

Very likely all three of the above causes are more or less contributory to the divergence of results obtained for the values of the coercive force, but the writer believes that the magnetic viscosity plays by far the most important rôle.

V. PRESENT METHOD FOR MEASURING HYSTERESIS CONSTANTS

The method for determining the coercive force, therefore, has been revised. Referring again to the hysteresis loop (Fig. 1), suppose that the induction corresponding to a magnetizing force H_m is at B_m. Let the magnetizing field be reversed and at the same time resistance added to the primary circuit so that the galvanometer deflection indicates a change of induction approximately one-half of the total change from B_m to $-B_m$. As stated above, owing to magnetic viscosity, the induction may be at some point B_d while appearing from the galvanometer reading to be at H_c. Now pass quickly from B_d to $-B_m$ and back to H'_c. If B_d and H_c coincide, the net change of induction in passing through the semicycle will be zero; but if B_d and H_c do not coincide there will be observed a residual deflection of the galvanometer. By adjusting the auxiliary resistance, B_d and H_c can be made to coincide so that the net change in induction is zero. Going back to H_m and reducing to H_c it will be found that; if there is any effect due to viscosity, the ballistic galvanometer will indicate a value for the change in induction other than one-half the total

TABLE 2.—Effect of Magnetic Viscosity on Measurement of Magnetic Induction

No. 293, Norway iron			No. 301, tool steel			No. 297, Bessemer steel			No. C-18-11, 0.85 per cent carbon steel (annealed)			No. C-18-VI-B, 0.85 per cent carbon steel (quenched)		
H_m	B_1	B_2	H_m	B_1	B_2	H_m	B_1	B_2	H_m	B_1	B_2	H_m	B_1	B_2
68	17 300	15 000	56	13 800	12 400	63	16 950	14 500	34	12 300	9600	42	2400	2200
146	18 900	17 400	137	16 200	16 500	146	18 800	16 600	90	15 100	13 000	87	8100	6800
232	20 000	18 800	236	17 300	17 000	228	19 800	18 400	150	16 100	14 600	140	11 300	10 300
320	20 800	19 600	316	18 000	17 800	322	20 600	19 600	238	17 200	15 800	234	13 400	12 800
425	21 500	22 400	420	18 600	18 800	420	21 250	20 400	330	17 900	16 800	315	14 400	14 200
505	22 000	22 400	550	19 200	19 400	550	21 800	20 900	430	18 500	18 200	495	15 800	15 500
695	22 300	23 200	670	19 600	19 800	690	22 200	21 800	515	19 000	18 400	670	16 850	16 700
740	22 700	22 800	885	20 300	20 300	845	22 500	22 200	690	19 700	19 000	840	17 600	17 400
900	23 000	22 800	1125	20 850	20 800	1060	22 900	22 400	860	20 200	20 000	1055	18 400	18 800
1180	23 600	24 000	1460	21 700	21 200	1330	23 400	21 600	1110	20 800	20 000	1330	19 350	19 400
1520	24 200	21 000	1870	22 600	21 500	.....	.....	.....	1280	21 200	20 000	1680	20 200	20 200
									1640	22 000	20 400	2230	21 550	20 800

B_1=Actual magnitude of B as one-half total change in induction from B_{max} to $-B_{max}$.
B_2=Apparent magnitude of B as read from galvanometer when the induction is changed from the maximum induction to zero.

change from B_m to $-B_m$. Table 2 gives for comparison values (B_2) obtained in this manner and the actual values (B_1) as obtained by taking one-half the deflection for complete reversal of B. It will be observed that the discrepancy decreases with the hardness of the material.

To accomplish the procedure just described a special gang switch has been devised so that one throw of the switch causes the induction to change from its maximum value to zero, and upon throwing back to change from zero to its maximum negative value and back again to zero. After this adjustment is made the process is repeated with the H coils connected in series with the galvanometer. The coercive force which is one-half the change in H from H_c to H'_c is then read directly.

TABLE 3.—Coercive Force and Residual Induction as Obtained by Different Apparatus

Sample No.	Material	H_{max}	H_c			B_r		
			Burrows permeameter	Fahy permeameter	High induction apparatus	Burrows permeameter	Fahy permeameter	High induction apparatus
293	Norway iron	100	1.61	2.4	1.5	8480	10 000	10 200
		150	1.70	2.5	2.0	8580	10 400	11 700
		200	1.75	2.8	2.0	8600	10 700	12 700
		250	1.72	.....	2.0	8670	.....	13 200
294	do	100	1.85	2.4	1.5	8250	9660	9850
		150	1.85	2.5	2.0	8250	10 100	11 000
		200	1.80	2.6	2.0	8250	10 600	11 950
		250	1.85	.....	.....	8250	.....	12 700
297	Bessemer steel	100	4.95	5.2	5.0	11 720	12 500	11 000
		150	5.0	5.4	5.0	11 740	12 600	12 000
		200	5.0	5.6	5.5	11 800	14 900	12 700
		250	5.05	.....	5.5	11 800	.....	13 200
298	do	100	5.1	5.2	5.5	11 500	12 400	11 300
		150	5.0	5.6	5.5	11 500	12 700	12 400
		200	5.2	5.6	6.0	11 500	13 000	13 000
		250	5.3	.....	6.0	.....	.....	13 400
301	Tool steel	100	13.2	13.0	13.0	10 900	11 250	10 400
		150	13.3	13.0	13.5	11 350	11 800	11 300
		200	13.5	13.4	14.0	11 500	12 000	11 800
		250	13.9	.....	14.0	11 600	.....	12 100
302	do	100	12.0	11.6	12.5	11 000	11 300	10 000
		150	12.5	12.3	13.5	11 350	11 800	10 900
		200	12.9	12.6	14.0	11 500	12 000	11 400
		250	12.9	.....	15.0	11 700	.....	.....
C-18-VI	0.85 per cent carbon steel, quenched in oil.	200	.....	42.8	45.0	.....	7990	7700
	0.85 per cent carbon steel, quenched in water.	100	44	42	42	6070	6200	6200
		150	48	46	44	7180	7250	6700
		200	50	48	49	7520	7750	7700
		250	53	49	52	7620	7800	8000

Table 3 gives values obtained in this manner (column 6) and compared with those obtained by the Burrows permeameter (column 4) and the Fahy permeameter (column 5). It will be observed that within the experimental error the values agree favorably. The observations in column 6, however, could not be read to as high precision as those in columns 4 and 5.

Since there is this favorable comparison for low magnetizing forces, it may be assumed that results are correct for high field values also.

As regards the measurement of the residual induction, it was concluded after repeated trials that, owing to errors inherent in the methods, the method already in use could not be improved

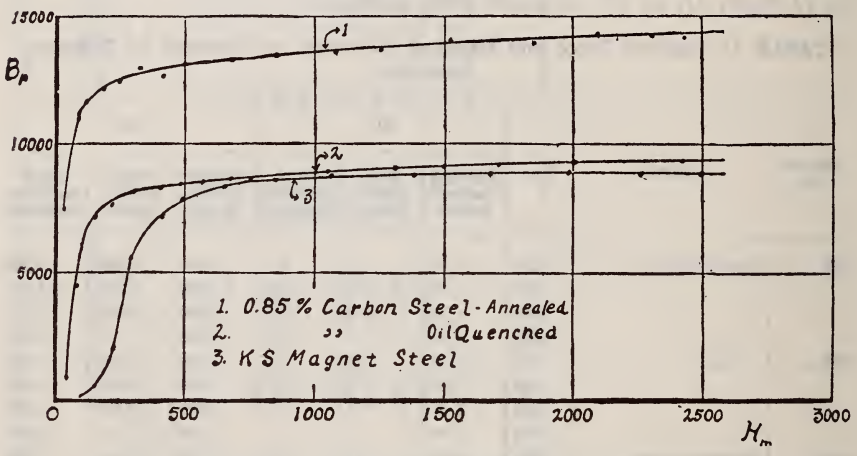

FIG. 2.—*Variation of residual induction with magnetizing force for three specimens of steel*

upon. For soft materials the values are too high, but for harder materials they vary only slightly from the true value. In Table 3, columns 7, 8, and 9, are shown the residual induction as obtained by the three types of apparatus.

In Fig. 2, the residual inductions, and in Fig. 3, the coercive forces for successive maximum magnetizing forces up to $H = 2500$ are shown graphically for three particular specimens, viz, eutectoid steel (0.85 per cent carbon) in the annealed condition, same steel when quenched in oil, and a remarkable magnet steel known as K S magnet steel and prepared by Prof. Honda. It will be observed that both curves resemble in shape the intensity of magnetization curve.

VI. SUMMARY

This paper consists primarily of a discussion of:

1. An earlier attempt to measure hysteresis values by means of a modification of the "isthmus method" and described by the writer in a former paper.

2. Possible causes for discrepancies which appeared in the results as compared with those obtained on other types of apparatus.

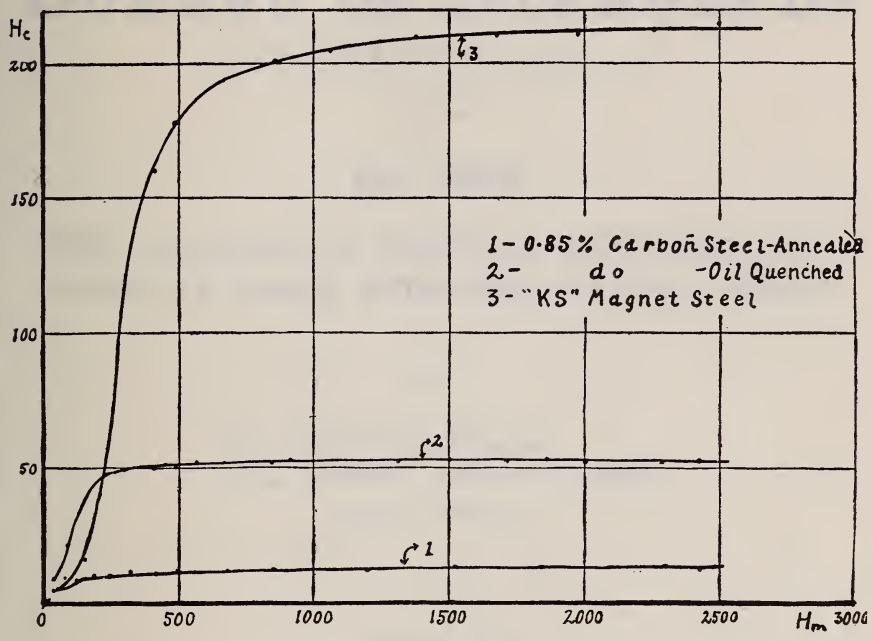

FIG. 3.—*Variation of coercive force with magnetizing force for three specimens of steel*

3. A new method of measuring the coercive force by means of this same apparatus.

Graphs are given which show the coercive forces and the residual inductions from successively higher maximum magnetizing forces plotted against the latter as the independent variable up to a field of $H = 2500$ gausses.

WASHINGTON, March 29, 1920.